ENERGY RECOVERY DEVICES IN REVERSE OSMOSIS

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ABSTRACT

Membrane desalination is a pressure-driven process. A significant amount of the energy imparted into the feedwater flowing to the reverse osmosis (RO) membranes leaves the membranes in the concentrated reject water. Positive-displacement "isobaric" energy-recovery devices recover nearly all of this energy and return it to the process. These devices together with improved RO membranes have made desalination an affordable and widely-accepted technology deployed around the world. However, the optimization of these processes is a science still in its infancy.

This paper presents an overview of energy recovery devices for RO applications. Process energy consumption and operational flexibility are discussed. Simulations of RO system flows and pressures over a range of process conditions are considered with the goal of identifying opportunities for optimized system productivity and energy performance. Comparisons with operating RO systems are provided for verification.

INTRODUCTION

Reverse osmosis is a water desalination process used widely around the world. The osmotic pressure of a salt water solution is overcome with hydraulic pressure, forcing nearly pure water through a semi-permeable membrane and leaving concentrated reject behind. In seawater reverse osmosis (SWRO) systems, an operating pressure of 60 to 70 bar (870 to 1015 psi) is required. Typically 50 to 75% of the energy consumed by an SWRO plant is used to drive the motors of the high-pressure pumps (Mickols et.al. 2005).

Even at these pressures a maximum of approximately 50% of the available pure water can be extracted before the osmotic pressure becomes so high that additional extraction is not economically viable. The rejected concentrate leaves the process at nearly the membrane-feed pressure. The combination of the high required membrane-feed pressure and the high-volume reject stream has historically limited the deployment of large-scale SWRO to regions where power is inexpensive and abundant. Recent advances in energy recovery device technology, together with improved membrane technology and process operations, have reduced the energy required by SWRO to a level comparable to the energy required to pump and treat surface water in many locations (Dundorf et.al. 2007).

ENERGY RECOVERY DEVICES

A number of devices have been developed to recover pressure energy from the membrane reject stream and return it to the feed of the RO process.

Turbine Devices

Turbine-based, centrifugal energy recovery devices (ERDs), such as Pelton turbines or hydraulic turbochargers, have been employed since the 1980s. A typical RO process with a turbine is illustrated in Figure 1.

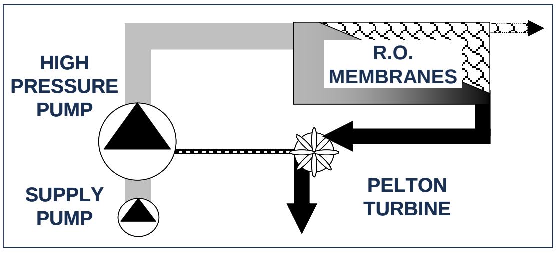

Figure 1: RO Process with a Turbine ERD

The membrane concentrate is ejected at high velocity through one or more nozzles onto a turbine wheel. The turbine, coupled to the high-pressure pump shaft, assists the motor in driving the pump that pressurizes the RO system. Energy consumption in the high-pressure portion of an RO system equipped with a turbine ERD is the energy required by the high-pressure pump motor. It can be computed by subtracting the energy recovered by the turbine from the hydraulic energy in the high-pressure pump discharge and dividing by the pump and motor efficiency as illustrated in Equation 1 (Stover 2008).

$$\text{Energy} = \frac{Q_{HP} \times P_{HP} - Q_{R} \times P_{R} \times \eta_{T} \times \eta_{HP}}{\eta_{HP} \times \eta_{HPM}} \quad (1)$$

Q_{HP} is the high-pressure pump flow rate, P_{HP} is the high-pressure pump differential pressure, η_{HP} is the high-pressure pump efficiency, Q_{R} is the turbine flow rate, P_{R} is the turbine differential pressure, η_{T} is the turbine efficiency and η_{HPM} is the high-pressure pump motor efficiency. Pelton turbines discharge at atmospheric pressure so P_{R} is, effectively, the membrane reject pressure.

Because energy is transformed twice, once by the turbine and once by the pump impeller, energy is lost. The water-to-water transfer efficiency of a turbine ERD system is the product of the turbine and impeller efficiencies, as shown in the second term in Equation 1. The component efficiencies range from 70% to a maximum of 90% (Hydraulic Institute). Therefore, the overall efficiency of a turbine ERD is typically 60 to 75%.

Isobaric Devices

To avoid the efficiency losses associated with the energy-transformation inherent in turbine ERDs, engineers developed positive-displacement isobaric devices for RO. These devices have been deployed widely since about 2002. They place the RO reject and the seawater feed in contact inside pressure-equalizing, or isobaric, chambers. There are currently two commercially-available types of isobaric ERDs including several piston-type work exchangers and the rotary PX Pressure Exchanger device. Piston-type devices have large chambers, pistons separating the concentrate and feedwater, and valves and control systems to switch flow between the chambers and limit the travel of the pistons. The PX device has small chambers, no pistons and no direct controls. Piston-type work exchangers were historically considered to be better suited to large SWRO trains because of their relatively large unit size. However, the largest SWRO trains operating today, 25,000 m^3/day in Hamma Algeria, are supplied with PX devices operating in arrays (Stover et.al. 2007).

Like reciprocating pumps, the positive-displacement pressure transfer mechanism used in isobaric ERDs deliver high efficiency despite pressure and speed/flow rate variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs. Many plants built with centrifugal ERDs have been retrofitted or their operators are considering converting to isobaric devices to reduce energy consumption and increase production capacity (Stover, Cameron 2007).

A simplified process flow diagram of an SWRO process with isobaric ERDs is shown in Figure 2. Concentrate rejected by the membranes flows to the ERD(s) driven by a circulation pump. The ERD replaces the concentrate with seawater. The pressurized seawater merges with the discharge of the high-pressure pump to feed the membranes. Water leaves the process as permeate from the membranes or as spent low-pressure concentrate from the ERD. An energy recovery efficiency of 98% can be achieved with state-of-the-art isobaric ERDs (Stover 2006).

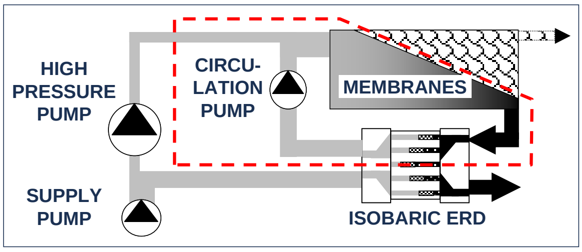

Figure 2: SWRO Process with Isobaric ERDs

The energy consumption in an RO system equipped with an isobaric ERD is the sum of the energy consumed by the high-pressure pump and circulation pump motors. It can be computed using Equation 2.

$$\text{Energy} = \frac{Q_{HP} \times P_{HP}}{\eta_{HP} \times \eta_{HPM}} + \frac{Q_{CP} \times P_{CP}}{\eta_{CP} \times \eta_{CPM}} \quad (2)$$

Q_{CP} is the circulation pump flow rate, P_{CP} is the circulation pump pressure and η_{CP} is the circulation pump efficiency, η_{CPM} is the circulation pump motor efficiency and the rest of the variables were defined above. It should be noted that the efficiency or performance of the isobaric ERD is not directly included in the energy consumption equation, rather it appears implicitly as a reduction in the high-pressure pump flow rate, Q_{HP}.

Equations 1 and 2 quantify only the energy consumed in the high-pressure portion of the SWRO proces, but this typically accounts for most of the energy consumed in the process. Also, the energy required in pre- and post-treatment is substantially independent of ERD type.

ERD Performance Comparison

A direct comparison of the performance of various ERDs using SWRO field data is virtually impossible because of inherent differences between systems and operating conditions. However, hypothetical systems can be considered for the sake of comparison. The equations for computing energy consumption in SWRO systems given above were applied to a medium-size system of 1,000 m^3/day and a large system of 10,000 m^3/day permeate flow, both operating at 45% membrane recovery and 69 bar membrane feed pressure. The results are shown in Table 1:

Table 1: SWRO Specific Energy (kWh/m^3)

ERD TYPE	MEDIUM SYSTEM	LARGE SYSTEM
Pelton Turbine	4.32	2.72
Turbocharger	4.26	2.69
Isobaric ERD	3.09	2.22

The benefit of ERDs for overall SWRO process energy reduction is illustrated in Figure 3.

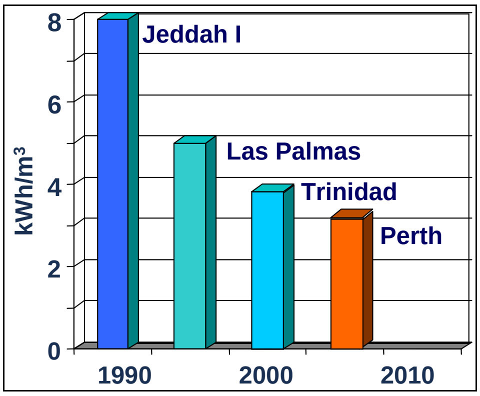

Figure 3: Evolution of SWRO energy consumption

Starting with the Jeddah 1 plant in Saudi Arabia which had no energy recovery and consumed over 8 kWh/m^3 in the SWRO portion of the process (Hassan et.al. 1991), SWRO energy consumption was first lowered by implementing Francis turbines as was done in Las Palmas, Gran Canaria (Talo et.al. 2007), then by Pelton turbines as was done in Trinidad (Thompson et.al. 2005). It should be noted that the Pelton turbines in the Trinidad plant are very large and considered state-of-the-art. Nevertheless, the isobaric ERDs and other process improvements cut SWRO plant energy consumption from approximately 3.8 kilowatt hours per cubic meter of permeate produced (kWh/m^3) to 3.2 or about 16% (Sanz, Stover 2007).

These data show that isobaric ERDs can reduce the energy consumption of a SWRO system by as much as 60% compared to a system with no energy recovery device, or by as much as 30% compared to a system with a turbine ERD. Since energy consumption can comprise as much as 75% of the total operating costs of SWRO plant, it has become almost inconceivable to build one without using isobaric energy recovery technology.

OPTIMIZING SWRO OPERATION

Isobaric ERDs separate the high- and low-pressure streams and seal the high-pressure portion of the process. To illustrate how this affects SWRO system operation, a dashed-line box is drawn around the high-pressure portion of the process and through the ERD in Figure 2. Nearly all the water that enters the dashed-line box from the high-pressure pump leaves as permeate. A small amount, less than 1% of the reject concentrate, is lost through the ERD. High-pressure pump flow and permeate flow are always nearly equal in isobaric-device-equipped SWRO systems regardless of membrane pressure or booster pump flow rate.

Membrane Recovery Variation

Membrane recovery is defined as the ratio of the permeate flow rate and the membrane feed flow rate. In SWRO systems equipped with isobaric ERDs, membrane recovery can be adjusted by varying the speed of the circulation pump with a variable frequency drive (VFD). This changes recovery, not by altering the permeate flow rate, but by altering the membrane-feed flow rate.

With reference to Figure 2 above, if the flow rate of the circulation pump is set with a VFD to be equal to the flow rate of the high-pressure pump, the system will operate at 50% recovery. If the flow rate of the circulation pump is increased to double the flow rate of the high-pressure pump, the system will operate at 33% recovery. As recovery rate is reduced, membrane pressure reduces and the load on the high-pressure pump motor reduces. As recovery rate is increased, membrane pressure increases but the SWRO system requires less feedwater. Such adjustments can significantly change membrane performance but have negligible affect on isobaric ERD performance which provides high efficiency regardless of flow rate or pressure. Although the maximum flow rate through each energy recovery device is limited, additional units can be added or removed as necessary to accommodate a wide range of recovery rate variation.

Membrane Recovery Optimization

The optimum membrane recovery rate depends upon the energy consumption rates, the price of power, other operating costs and the cost of equipment. A hypothetical optimization chart is shown in Figure 4. These data assumed a feedwater salinity of 36 grams per liter; high-rejection, low-energy, 400 square-foot membranes; and 12,000 cubic meters per day permeate production.

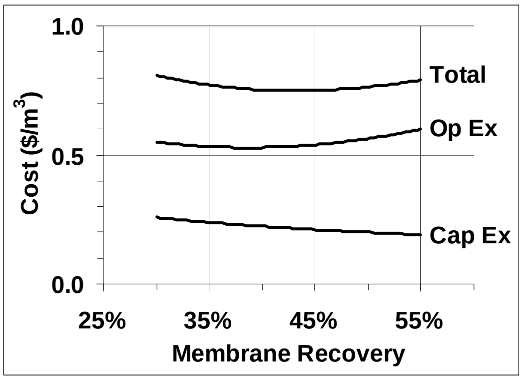

Figure 4: Membrane Recovery Optimization

In Figure 4, the operating expense (Op Ex) is shown as the total cost over a 20 year plant life divided by the amount of fresh water produced. The minimum cost per cubic meter produced is shown at 39% membrane recovery but can vary from 36 to 42% depending upon the feedwater salinity, membrane performance and system capacity. To the left of the minimum, pretreatment, supply pumping and circulation pumping costs increase. To the right of the minimum, the higher osmotic pressure results in increased energy consumption by the high-pressure pump.

The capital expense (Cap Ex) line in Figure 4 varies monotonically with membrane recovery. At higher recovery rates, more water is produced with the same equipment, so the cost per unit of water produced decreases. The Total line in Figure 4 is the sum of Op Ex and Cap Ex. Its minimum is slightly to the right of the Op Ex minimum, ranging from 40 to 46% recovery depending upon other feedwater and process variables. Accordingly, most SWRO plants being built with isobaric ERDs today operate at 40 to 46% recovery.

Although Figure 4 is a hypothetical example, the ratio of Op Ex to Cap Ex is consistent with most currently operating SWRO plants. Operating costs usually exceed capital costs by a factor of 2 or 3 over a 20 year plant life (Mickols et.al. 2005).

There are reasons other than energy minimization to adjust membrane recovery. For instance, if membrane fouling conditions occur or the membranes get old and compacted, the recovery rate can be lowered to increase membrane cross flow, reduce contaminant deposition and biological growth on membrane surfaces and reduce the osmotic pressure in the membranes. Alternately, if there are pretreatment problems, recovery can be increased so that less feedwater is consumed to produce nearly the same amount of permeate. In these ways, an operator can manipulate and optimize SWRO system performance to achieve low energy consumption and high productivity throughout the year and over the course of a plant's life. Flexible recovery operation is a tremendous advantage provided by isobaric ERD technology.

Other SWRO Optimization Techniques

Isobaric ERDs and the high-pressure pump operate independently in SWRO processes. There are several ways to take advantage of this fact to reduce energy consumption and increase process performance. For example, one high-pressure pump can be used to feed multiple SWRO trains that are each equipped with dedicated ERD devices or arrays. In this way, larger, more efficient high-pressure pumps can be employed while the trains can be individually manipulated (Sanz, Stover 2007).

The high-pressure pump and the ERDs can be fed with different supply streams to minimize the supply-pump energy required. The ERDs require a supply pressure of only 2 bar in most process designs. However, net positive suction head (NPSH) requirements for high-pressure pumps may require a feed pressure greater than 3 bar. The high-pressure pump may also be fed at an even higher pressure with a booster pump driven by a motor with a VFD. This allows the high-pressure pump output to be varied without the expense of a large VFD on the high-pressure pump motor. Furthermore, if the process provides a high NPSH, the high-pressure pump can be designed to run at a higher efficiency.

Because the flow rate of pressurized water from the device can be different from the flow rate of low-pressure water fed to the device, PX devices uniquely provide an additional degree of freedom to RO process operators. For example if the circulation pump speed is increased with no other changes to the SWRO process, membrane recovery decreases while system recovery stays the same. Such changes make the membrane recovery rate and the system recovery rate different. Although operating with such "unbalanced" flows results in a salinity increase at the membrane feed, membrane feed pressure can actually be reduced, resulting in energy savings. Table 2 presents data from a model process under different ERD flow ratios.

Table 2: Model SWRO Process Performance with Unbalanced PX Device Flows

	Balanced (LP = HP)	**Lead Flow (5% more LP)**	**Lag Flow (5% more HP)**
Membrane Pressure (bar)	63.2	63.0	62.7
Feed Salinity (mg/l)	36,900	36,750	37,100

Permeate Flow (m^3/hr)	468	469	473

CONCLUSIONS

Isobaric ERDs can reduce the energy consumption of an SWRO system by as much as 60% compared to a system with no energy recovery or by as much as 30% compared to a system with a turbine ERD. As a result, most SWRO plants being built today use isobaric ERDs.

Isobaric ERDs provide high constant energy transfer efficiency over a wide range of flows and pressures. The membrane recovery rate of SWRO processes equipped with these devices can be manipulated relatively easily by adjusting the speed of the circulation pump and the amount of low-pressure water supplied to the ERD. This allows the membrane recovery rate to be varied to optimize process performance and reduce energy consumption. This flexibility allows a process operator to optimize SWRO process performance as seasonal variations in the seawater occur or as the membrane elements age. Numerous best-efficiency operating points can be found which is a tremendous advantage for low-cost SWRO operation.

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